NASA TT F-11,429

NASA TT F-11,429

HISTORY OF AVIATION AND COSMONAUTICS, VOL. III

N. D. Anoshchenko, Ed.

Translation of "Iz istorii aviatsii i kosmonavtiki, Vyp. 3." USSR Academy of Sciences. Soviet National Association of Historians of Natural Science and Technology, Moscow, 1965.

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
WASHINGTON, D.C. 20546 NOVEMBER 1967

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RUSSIAN HISTORY OF AVIATION AND ASTRONAUTICS VOLUME 3

N. D. Anoshchenko et al.
Editors

FROM THE EDITORS

This publication concerns the development of the theory of ramjet engines and the first aircraft with engines operating on the basis of this theory. /3*

The date of the creation of the theory of air-breathing jet engines is usually considered 1929, the year in which Academican B. S. Stechkin's classic work appeared. This work served as the theoretical foundation in the development of all types of air-breathing engines, including ramjets.

Shortly after Stechkin's work was published, GIRD (Group for the Study of Jet Engines) in 1932 began engineering history's first experimental investigations of air-breathing jet engines, both on test stands and in flight, for which an experimental ramjet engine was installed in the body of an artillery shell.

The GIRD work continued with the development and flight-testing of rockets with air-breathing jet engines and ramjet-powered aircraft in which the engines were installed as auxiliary motors in aircraft designed by N. N. Polikarpov and A. S. Yakovlev.

An article in this collection is dedicated to each of these stages of the first period of work in the field of ramjet propulsion. Each article sets forth the basic facts and chief technical characteristics of the engines' construction.

The question of the present and future use of ramjet engines plays an important role in the evaluation of the significance of the ramjet theory. Therefore, along with the material on the history of ramjets, this collection contains two articles on the state-of-the-art and future development of the engine. The first theme is discussed in the article by Professor M. M. Bondaryuk, in which he gives a clear picture of the transformation of Stechkin's theory into actual modern ramjet-propelled aircraft. In his own article, Academician Stechkin has given a scientific prognosis of the future development of ramjets and their use in various craft.

The materials are reports presented 5 March 1964 at the joint meeting of the Aviation and Space History section of the Soviet National Union of Historians of Natural Science and Technology of the USSR Academy of Sciences, All-Union Committee on Astronautics of the USSR DOSAAF (All-Union Cooperative Society for the Assistance of the Army, Air Force and Navy) and the M. V. Frunze Central House of Aviation and Astronautics. The article by Academician Stechkin was published in the journal "Aviation and Astronautics (Aviatsiya i Kosmonavtika)", No. 1, 1965. /4

* Numbers in the margin indicate original pagination in the foreign text.

As was stated above, the collection contains materials on only the first years in the history of ramjets. It does not include material on the later development of the theory of ramjets in the works of Soviet and foreign scientists, nor the wide experimental studies which have served as a basis for the modern development of ramjets. During the time preceding the publishing of the theory of air-breathing jets, as is witnessed by the extensive world literature, there were detailed experimental studies of ramjets and their components. Special attention was devoted to the study of the process of fuel consumption and the processes in the combustion chamber, studies of air-intakes for supersonic ramjets, and the development of ramjet control methods and systems. The structural tests preceding the development of high-efficiency ramjet engines have an exceptional importance. All these questions are to be clarified in later editions of the collection.

RAMJET ENGINES FOR SPACECRAFT

B. Stechkin

N68-13567

The ramjet has a definite area of application. It is presently felt that the ramjet can be expediently used for flight at Mach numbers within the limits $1.5 \leq M \leq 7$, and there is reason to believe that the upper limit can be substantially increased (to $M \cong 10$-12). At $M \leq 1.5$, the thermal efficiency in the ramjet cycle is quite low, as a result of which its specific thrust and fuel economy are too low to permit efficient practical use. At high velocities ($M > 12$) the intake diffuser operates ineffectively and due to kinetic energy losses by the air, the combustion chamber temperatures becomes critically high. Progress hinges on our success in carrying out combustion at a high speed of air motion, so that the air entering the craft will be at least partially braked. There are also great hopes of using the ramjet with a liquid hydrogen propellant. /5

The use of the ramjet at space-flight speeds ($M \geq 28$) at altitudes of 90-100 km, as is necessary for oxygen buildup, for example, is still impossible. Future progress in the development of the ramjet can be foreseen due to the transfer to external (outside the craft) combustion accomplished at air speeds as high as desired.

Thus, the use of ramjets for spacecraft can presently be seen for rocket launching within a continuous atmosphere to speeds from $M = 7$-10. Launching may be effected either on a particular craft circling the Earth or directly on the rocket itself, in the first stage. Supplying air for the afterburning of rocket engine gases in rocket flight increases thrust, but this will not hold with the ramjet.

We will find a substantially wider field of application for the ramjet in the area of high-speed aircraft and in rockets not to be used in space flight.

35 YEARS AFTER THE CREATION OF THE THEORY OF AIR-BREATHING JET ENGINES BY ACADEMICIAN B. S. STECHKIN

Yu. A. Pobedonostsev

The rapid development of modern aviation, especially in its most recent period, is characterized primarily by the wide application of jet engines in aircraft. /6 As a result of the transfer from piston to jet engines, aircraft flight speeds have multiplied. Jet engines have permitted manned flight in the atmosphere exceeding the speed of sound.

Of various types of jet engines, the air-breathing jet engine has attained the greatest application in present-day aviation.

As early as the middle of the last century, in 1867, Staff Captain N. A. Teleshov invented an engine which he named the "thermal air-blower" and which embodied the basic elements of the modern ramjet. Diagrams of similar engines abroad appeared substantially later, only in the first decade of the Twentieth Century.

In 1909, the Russian engineer N. V. Gerasimov evolved a design for a jet engine in which he planned to use a gas turbine as an air-compressor drive. It is noteworthy that the first models of this apparatus were built in our country by P. D. Kuz'minskiy in 1892-1897 and by V. V. Karavodin in 1908. The combustion chamber in the Karavodin turbine was in essence the first resonance-pulse jet.

In 1911, the engineer A. Gorokhov proposed a plan for an engine-compressor air-breathing jet engine. In this engine he proposed preliminary compression of the air in front of the combustion chamber in a compressor driven by a turbine engine.

The plan for an aircraft piston engine with turbine drive was first proposed in 1914 by the Naval Officer M. N. Nikol'skiy. The turbine was to have /7 been turned by gases flowing from a liquid-propellant rocket engine.

The idea of a ramjet engine was first advanced (1907-1913) by the French engineer Rene Laurent. However, its first theoretical development, structural design as well as the tests with ramjet engines were accomplished much later by our Soviet specialists.

Much effort was directed toward the theoretical and engineering tests of this apparatus, as well as its application to a large number of aircraft, with the aim of aiding their takeoff from the Earth's surface. This was accomplished by one of the pioneers of interplanetary travel and rocket technology--Fridrikh Arturovich Tsander.

The first references to jet engines are in his 1922 dictations, which have been collected. In his investigations, Tsander gave great importance to the use of the terrestrial atmosphere to facilitate launching heavily loaded spacecraft. He strove to eliminate the necessity of carrying an oxidizing agent on the rocket in the dense atmospheric layers of the Earth's surface. However, fuel consumption is quite high at the beginning of the spacecraft's motion, during launch. Its flight speed is quite low with respect to the speed of gas exhaust from the rocket nozzles. Therefore, the dynamic efficiency of rocket is insignificantly low, while at the same time the initial launch weight is at its highest. Consequently, it is precisely at the beginning of the spacecraft's motion that the greatest expenditure of heavy fuel occurs.

Freedom from the need to supply the jet engine with a heavy oxidizing agent on the first part of its flight promises great possibilities for lightening the launch weight of the craft. If atmospheric oxygen is used during takeoff, the reduction in the craft's weight and dimensions will be substantial. Tsander understood this very well much earlier than others. He carried out in-depth theoretical investigations on the thermodynamic cycle of such engines and arrived at an interesting new conclusion that the relatively low efficiency of jet engines at low flight speeds might be significantly increased through great overexpansion of combustion products leaving the engine exhaust nozzle at supersonic speeds and their subsequent compression simultaneous with cooling to pressures of the surrounding medium which the final products of combustion enter. Tsander called /8
this specialized setup a "reverse cone." However, in those days to those in gasdynamics it was still unclear how such compression could be effected without great energy losses from the gas flowing at supersonic speed. All tests to attain such compression with low losses had poor results. Only in the 1940s did the first practical studies in this direction yield good results. Only very recently were actual structural diffusers created which yielded compression with high efficiency in the supersonic gas flow.

In 1923, the Soviet engineer V. I. Bazarov perfected his design of a gas-turbine engine with a centrifugal compressor. The Bazarov design incorporated all of the basic features of modern gas-turbine engines. In his engine, atmospheric air reached the centrifugal compressor through an intake duct. From the compressor it progressed to the combustion chamber, where it was divided into two flows, one of which was used for fuel burning, while the second was admixed to the combustion products to lower their temperature before they reached the turbine blades. Passing through the turbine, the gases flowed out through the nozzle at high speeds. The power of the turbine in the Bazarov engine exceeded the required compressor power. Its excess was used for turning the air propeller. Thus, the full engine thrust consisted of the thrust of the propeller with the reactive force of the gases flowing from the nozzle.

In 1924, B. N. Yur'yev developed a design for a reaction propeller. The hub of this propeller had a central opening through which air entered. To obtain high economy, the air was initially compressed by the centrifugal compressor rotated by the propeller itself. Passing through the intake opening, the air hit the tubular blades of the propeller. Moving around the blades, the air was additionally compressed by centrifugal force. At the end of the blades, fuel ignited at high temperatures was injected into the compressed air.

The combustion products flowed out into the atmosphere from the nozzle placed at the end of the blades and created a reactive force which turned the propeller.

Each year the work of Soviet innovators broadened. Foremost scientists, designers and inventors worked diligently to give our aviation new, light and /9 small but powerful engines capable of giving it further impetus toward attaining greater and greater speeds. This creative work of the Soviet specialists allowed us to define the basic contours of future jet engines. But there was a lack of a fundamental general theory--the bases for future design operations and in-depth theoretical investigations in this region.

For a correct, efficient realization of the bold plans of our designers, the theoretical basic plans of our designers the theoretical bases for designing the various jet engines themselves had to be evolved.

In response to this urgent need on the part of the designers and the requirements for developing our aviation, Soviet science also succeeded in solving this fundamental challenge.

In 1928, one of the closest successors of N. Ye. Zhukovskiy, today Academician Boris Sergeyevich Stechkin, was lecturing on hydrodynamics at the Mechanics Department of Moscow's Bauman Higher Technical Institute. "One day, in December of 1928," recalls one of the former students of that period Stepan Aleksandrovich Aksyutin, "Stechkin turned to the students and offered to tell them 'something new and interesting'."

As you might imagine, the students, who along with Aksyutin included Anan'yev, Kamenomostskiy, Knyazev, Krichevskiy, Lavochkin, Sokolov, Tayts, and others, readily agreed. He then began to set forth a new theory he had developed on rocket engines. With all the rigor of classical gasdynamics he set up equations for the thrust and efficiency of engines operating in an expandable medium in the most general case.

For a noncompressible fluid without considering heat the question of the force of the reaction of the jet, a fluid, passing through a jet engine was comprehensively developed earlier by N. Ye. Zhukovskiy and set forth in his classical works "Reactions of Inflowing and Outflowing Fluids" and "The Theory of Vessels Set into Motion by the Force of a Water Jet."

Similar investigations were first performed by B. S. Stechkin for the flow of an elastic medium.

He analyzed in detail the question of supplying energy to an airstream in an apparatus and concluded that the law of the relationship of heat to air can be arbitrary but the integral performing the work must be taken in terms of a closed contour in the coordinates pv representing the change in the state of /10 the air passing through the apparatus.

Thus, the thermal efficiency of the heat cycle undergone by air in a jet engine during its contact with air there was immediately determined. The full efficiency of the jet engine was found to be a product of the thermodynamic efficiency and engine efficiency or, as it is now usually called, "motion efficiency" or "propulsive efficiency."

At the end of the lecture Boris Sergeyevich gave a quantitative definition of the full efficiency of an air-breathing jet engine for flight speeds of 50 to 600 m/sec powered by hydrocarbon fuel with a coefficient of air excess of $\alpha = 2$ and thermal cycle efficiency of $\eta_t = 0.25$.

In addition, he showed how the efficiency for the air-breathing jet will be determined if energy is supplied to the air either partially or fully, and he examined the case of the compression of the air stream from losses of the kinetic energy of the incoming flow. In this case the air describes the "Brayton cycle" and its thermal efficiency will equal the difference between unity and the temperature-air ratio at the end of compression to its initial temperature upon entry into the jet engine.

Word of this lecture quickly spread among the top scientific and engineering brainpower then interested in rocket theory, and Stechkin was invited to repeat his lecture before a larger group.

Such a lecture took place soon after in one of the large auditoriums of the House of the Soviet Army. The hall was overflowing, and many wishing to enter could not. Then Boris Sergeyevich was requested to publish his lecture. And so, at an extraordinarily fast pace, with the aid of Stechkin's students, the lecture was polished and on its basis Boris Sergeyevich prepared for press the article "The Theory of the Air-Breathing Engine,." It was first published in February 1929 in the journal "Tekhnika Vozdushnogo Flota (Air Force Engineering)" and thus became the property not only of us in the USSR, but of those in other countries as well.

This article was the first time that the equations of thrust for a jet engine were published:

$$R = m\,(v - v_0) + f\,(P - P_0)$$

$$R = m\,(v - v_0)$$

Clarifying the principles of operation of the air-breathing jet engine, Stechkin wrote: /11

"Force R, which we will call the free thrust of the reactive engine, will thus be the equivalent force of air pressure on both the internal and external surface of the jet engine."

The article gave the equation for engine efficiency:

$$\eta_e = \frac{RV_0}{Q_0 A} = \frac{2V_0}{V + V_0}\,\eta_t$$

and stated:

"As may be seen, the efficiency of the reactive engine equals the product of two efficiencies, one of which is the thermal efficiency of the air cycle and the other is the efficiency of a propeller moving with speed v_0 and throwing behind a stream of air with absolute velocity $v - v_0$."

Further in the article the following expression for the efficiency of the air-breathing engine was given:

$$\eta_e = 2\eta_t / \left(1 + \sqrt{1 + \eta_t \frac{2gQ_0}{AV_0}}\right)$$

The theory of the air-breathing engine developed by Stechkin pertained not only to the ramjet but to engines with compressors as well. In the article quoted it was written:

"If there is contact with external forces when the air passes through the engine, the efficiency has the form:

$$\eta_e = \frac{RV_0A}{Q_0 + AT_0}$$

where T_0 is the force spent outside for the contact with each kilogram of force of air equal to T."

Shortly after Stechkin's work was published, the foreign engineering literature referred to it and acknowledged unanimous recognition of the Soviet supremacy in this field. Thus, for example, the well-known Italian scientist in hydrodynamics Arturo Giovanni Crocco in his essentially new work "Superaviation and Hyperaviation," published in 1931 in "Rivista Aeronautica" had to acknowledge that the classical theory in air-breathing engines was due first to Soviet Professor Boris Sergeyevich Stechkin.

Stechkin supplemented his remarkable contribution to the development of jet engineering, as was indicated earlier, by much pedagogical work. Passing /12
his knowledge on to hundreds of young specialists, Stechkin furthered the wide introduction of works on jet engines to the industrial design offices, research institutes, test stations and other organizations. Abstracts of Professor Stechkin's lecture, which he read at Moscow's Bauman Higher Technical Institute, in the N. Ye. Zhukovskiy Air Force Academy, and at special engineering-design courses on rocket technology, served as the theoretical manual for the design of air-breathing engines.

In the early 1930s, the editorial staff of the paper "Za industrializatsiyu (Industrialization)" organized another lecture by Boris Sergeyevich Stechkin on this same theme in his quarters on Tsvetnoy Bul'var in Moscow.

Thus, the theory of the air-breathing engine created by B. S. Stechkin began its full life and permeated many design offices specializing in this realm as well as scientific research and planning organizations.

Now we are witness to the wide use of large craft powered by jet engines such as the airliners of A. N. Tupolev, passing through the air above our planet at incredible speeds, and the value of B. S. Stechkin's theory is more and more understood.

I personally see broad horizons for these engines not only in aviation, but also in rocket technology--and their use in the first stages of ballistic missiles and, as was brilliantly predicted by F. A. Tsander in his day, on winged rockets.

Already the first calculations and studies of their application to rockets indicate that the value of various complex engine structures has caused a substantial drop in the initial launch weight of the rocket and on-board fuel reserves, which is especially desirable for large carrier rockets lifting heavy craft into orbit.

SUPPLEMENT TO THE THEORY OF ACADEMICIAN B. S. STECHKIN
ON THE CREATION OF RAMJET ENGINES

M. M. Bondaryuk N68-13569

The development of engine installations for aircraft in the last 15 to 20 years has been characterized by spasmodic processes. In a relatively short time there occurred the formation, blossoming and decline in the development of various types of air-breathing engines (piston, pulse jet, turboprop, turbojet and ramjet). /13

The ramjet encompasses the widest range of application in terms of flight speed and altitude. It is well-known that as flight altitude increases and is accompanied by a drop in atmospheric pressure, conditions for carburation and fuel consumption in the combustion chambers of air-breathing jets degenerate. On the other hand, with an increase in flight speed through the use of high-speed pressure heads for the inflow, there is a pressure increase in the combustion chamber. Therefore, the greater the flight speed, the higher the altitude at which combustion can satisfactorily occur. And because the ramjet is capable of developing the highest speeds, it can operate at higer altitudes than any other type of air-breathing jet engine. Therefore, supersonic and hypersonic ramjets are being given the greatest future in today's world literature for being the engine most capable of powering winged aircraft. These same engines can be effectively used for wingless rockets as well for the power source of the second stage (ref. 4).

If winged flight is considered at top speed for relatively long periods, the only solution to the problem is use of the ramjet.

The development of ramjets is affected by the fact that with increase in flight speed, the air-breathing jet engine has difficulty and the optimal values of pressure increase in the compressor must be lowered. Thermodynamically, the use of the turbojet is reasonable when pressure behind the turbine is greater than that in front of the compressor.

Theoretically, the degeneration of the turbojet occurs at Mach 4, at which point the optimal degree of pressure increase equals unity. The actual flight Mach number determining the danger point for a turbojet of usual design will hardly increase the Mach number M = 3 significantly and will depend on the degree of perfection of the engine parts and the overall design and engine structure. /14

Ramjet engines have already been used successfully in various aircraft. Examples are the Bomarc missile, which has been thoroughly described in the press; the long-range anti-aircraft guided missiles: Bloodhound, Telos, Vega, Matra, etc; winged rockets for ships and shore targets--Typhoon, etc; the supersonic drone aircraft: Lockheed Kingfisher, Beechcraft, Aeronca, Nord Aviation ST-41, etc.

This beginning of a wide practical application of ramjet engines is explained by their intrinsic advantages over other types of jets. Along with the ramjet's many basic advantages and its already mentioned capability of operating at very high flight speeds and altitudes, there is also its greater economy over the liquid-propellant rocket engine as well as its light weight, lack of moving parts and simple construction.

These properties have determined the ramjet's range of application; it is the most effective engine for high-speed aviation.

The limits of operation of the ramjet are functions of the flight speed and altitude. Altitude is determined by the Mach number and is the minimum required for the functioning of pressure in the combustion chamber. The maximum Mach number at which the ramjet can operate practically has not yet been established. In a very significant way it depends on the degree of dissociation of combustion products, on new types of fuel (alkyl boranes and hydrogen) and on the principles of organization of the operating process (combustion at Mach 1). With a significant increase in the Mach number, additional heat supply does not cause agreat increase in gas temperature, because the energy is expended in the dissociation of combustion products. CO_2 and H_2O molecule fragments appear in the combustion and discharge products. It must be noted that in any given case the effect of dissociation is contradictory. Being a negative effect causing disintegration of molecules and consequently a drop in temperature, dissociation at the same time is not an absolute loss, because recombination occurs during expansion and /15 escape of the products of combustion. At high flight speeds and consequently at high dynamic compression, recombination of the products during escape almost completely eliminates the deleterious effect of initial dissociation. Because energy expended in dissociation is freed during recombination, the escape velocity of gases increases. Consequently, at high Mach numbers dissociation limits the combustion temperature ($T = 2800 - 3000°$ K), which is favorably shown in the combustion chamber stability, and with this causes a considerable supply in heat energy, which is manifested by recombination in the nozzle sleeve. It is of course necessary to consider the slight decrease in the heat efficiency of the overall process, because the heat supply in the nozzle sleeve occurs at decreased pressure.

As has been stated above, the great advantage of the supersonic ramjet is its small specific weight. It is interesting to observe how weight is distributed among ramjet parts. In one engine with an overall weight of 140 kg, 40 percent was for the combustion chamber and nozzle, 34 percent for various components and 26 percent for the diffuser. It must be noted that the diffuser has a long duct necessary only for mixing. The specific weight of this engine is $0.2 \frac{\text{kg wt}}{\text{kg thrust}}$ at altitudes of $H = 18$ km and totals $0.02 \frac{\text{kg wt}}{\text{kg thrust}}$ for $H = 0$.

The idea of the use of jet engines on aircraft was expressed in the 1840s by the Russian engineer I. I. Treteskiy and in the 1860s by M. N. Sokovninyy. N. Ye. Zhukovskiy, in his works, comprehensively investigated the full reaction of escaping fluids and evolved a formula for determining the efficiency of the reactive engine.

Another great Russian scientist, K. E. Tsiolkovskiy, developed a theory of rocket flight with variable mass and derived a series of basic equations for the dynamics of rocket flight and proposed structural diagrams for rockets. In his works, he devoted special attention to liquid-propellant rocket engines. He also developed a diagram for an air-breathing engine.

In 1929, B. S. Stechkin's work "The Theory of a Reaction Engine," appeared. In it he gave the first calculations for various types of jet engines. After this, there appeared experimental and theoretical studies of the operation pro- /16
cesses of ramjet engines, theoretical investigations of their use on aircraft, and finally attempts for their practical application.

In the Soviet Union the idea for a ramjet engine was first applied by Yu. A. Pobedonostsev and M. S. Kisenko, who used a 76-mm artillery shell for the object and phosphorus for the fuel. Their tests obtained a notable increase in the distance of the shell's flight. This work is the first test of the practical use of the ramjet engine.

In 1939, the engineer I. A. Merkulov built and flight-tested a rocket with subsonic ramjet engines, and then aircraft ramjet engines for use as boosters for production aircraft.

In 1942, this author and G. A. Varshavskiy conducted similar tests on the LAGG-3 aircraft, which showed the practical workability of ramjet engines along with a whole group of faults which had to be eliminated to permit normal use of the engine.

Ramjets are characterized by the creation of the operating pressure in the combustion chamber through braking of the fast thrust of air entering the airscoop. Fuel combustion in the chamber occurs at almost constant pressure.

A natural intrinsic deficiency in ramjet engines is the lack of takeoff thrust and a poor economy at low flight speeds. For takeoff of ramjet-equipped aircraft the use of some takeoff device is required.

Ramjet engines may be divided into two basic groups: a) acceleration, and b) sustainers.

Acceleration engines are intended for the acceleration of rockets or aircraft and are designed such that they will yield maximal thrust within a wide range of Mach numbers and flight altitudes. Consequently, the acceleration engine must have a diffuser with sufficiently broad characteristics within a wide range of Mach numbers, a combustion chamber with minimal hydraulic resistance and increased thermal stability for operation at limiting thermal-stress operation regimes. As a rule such an engine has a large relative critical cross- /17
section ($f_{cc} \cong 0.9$) for the nozzle due to the rocket's requirements of maximum booster heating. It operates between Mach numbers from 1.5 to 5. Operation time is usually not great.

The sustainer engine is intended for winged-rocket flight or aircraft flight at constant speed over more-or-less long distances. Maximum economy is of course demanded of such an engine. The engine has a diffuser operating within a narrow range of Mach numbers but with high performance, a combustion chamber of mean thermal stress with thorough fuel combustion, and a Venturi-type expansion nozzle in which the basic transformation of potential and thermal energy of the flow into kinetic energy occurs.

There are acceleration/sustaining engines used on craft which must first attain acceleration to definite speeds and then maintain constant-speed sustained flight. This type engine has a so-called "compromise" diffuser, i.e., one capable of operating with high performance over a somewhat narrower range of Mach numbers than the acceleration engine, but which in return offers fairly good performance for sustained flight. Such an engine has less maximum thrust than the acceleration type and less economy at cruising flight than the sustained.

The combustion chamber of such an engine must operate with a wide range of mixture compositions. The engine has a Venturi-type expansion nozzle capable of operation at high booster heating.

If the acceleration/sustained engine must offer maximum thrust and economy parameters characteristic of both types engines separately, a controlled diffuser and nozzle with variable critical opening must be used.

The basic element of the ramjet engine is its combustion chamber, where the chemical energy of the fuel is transformed into the thermal energy of the gas flow, which within the limits of the combustion chamber partially succeeds in transforming into kinetic energy of the gas jet. The combustion chamber is a high-performance heating arrangement capable of consuming tens of kilograms of hydrocarbon fuel per second. Fuel consumption occurs at high air-flow speeds reaching 150 m/sec and pressures reaching several atmospheres. It is natural that the combustion chamber must have a powerful stabilizing setup supporting /18
constant combustion as well as devices assuring reliable ignition.

The combustion chamber must have a high fuel combustion ratio and minimum hydraulic resistance within a rather wide operation range with respect to mixture composition.

The high values for completeness of fuel combustion are attained by logical fuel distribution throughout the chamber, the positioning of the high-temperature local combustion focus, usually in the center of the combustion chamber, and an effective system of annular and radial structures for flame stabilization. The combustion chamber must have the required length within the limits of which thorough combustion of the fuel with a prescribed completeness occurs. The operation range of the combustion chamber depends on the demands made on the engine during operation. Thus, if the engine is an acceleration type, maximum thermal stress conditions exist in the combustion chamber which are characteristic of the combustion process with a coefficient of air excess of $\alpha \cong 1$ and high pressure in the operating body. In this case the so-called single-circuit setup is selected in the combustion chamber in which conditions with mixture composition of $\alpha \cong 1 - 2.2$ may be realized.

If the engine is a sustained-operation type it must offer maximum economy, and consequently the combustion chamber must operate at relatively weak mixture contents(α = 2.0 - 3.5 with respect to the cruising flight Mach number). In this case the combustor is double-contour. The internal contour operates on mixtures close to stoichiometric, and the outer contour is passed by the remaining portion of the air which when mixed with the internal heated combustion products creates the necessary limits of operation with respect to mixture composition.

The acceleration/sustained engine must have the properties of both types of engine; developing this type of engine is therefore quite a challenge.

Let us concentrate on several actual ramjet engines.

In 1948, the single-contour subsonic acceleration/sustained engine was created for use as a booster on the La-9 aircraft.

Two ramjet engines were suspended from the aircraft's wings and set into operation by the pilot. The engines operated within Mach ranges from 0.4 to 0.85 and generated 320 kg thrust at rated altitudes. The engine's specific thrust /19 under various regimes was 520-650 $\frac{kg}{kg/sec}$.

The ramjet engine yielded a maximum relative increase of 110 km/hr in the speed of the La-9 and could be fired repeatedly. Its dry weight was 40 kg.

Presently the scientific literature (refs. 3, 6, 7, 9) is devoting more and more attention to hypersonic engines, i.e., ramjets capable of operating at high supersonic speeds ($M > 5$). The interest in hypersonic engines is due to their capability of operating within a wide range of Mach numbers without control of the flow-passage cross-sectional areas of the engine. Of course, the usual supersonic ramjet engines are capable of operating within wide Mach number ranges; to do so their flow-passage areas must be controlled during flight, which is rather complicated.

The main advantage of the hypersonic ramjet is that heat supply to the air in the combustor occurs at supersonic flight speeds. Consequently, the hypersonic engine has no critical sections in its channel. This leads to the fact that the hypersonic ramjet engine, having an unregulated diffuser and venturi, can operate within much wider ranges of flight speeds and mixture compositions than the supersonic. Heat supply to the supersonic flow in a cylindrical tube is known to be accompanied by an increase in the static pressure of the flow and a drop in Mach number, i.e., a restriction of the temperature regime of the hypersonic engine for Mach 1. With additional supply of heat there is a decrease in the air consumption through the engine and a disruption of the system of shocks at the diffuser intake.

At first glance it appears strange that such relatively high performance can be expected of the hypersonic engine when it is well-known that with an increase in the flow velocity, losses in full pressure when heat is supplied increase sharply, while the ratio of pressure reduction is extremely small in the hypersonic diffuser.

However, it must be kept in mind that for high flight speeds, air compression in the compressor is so great that even high pressure losses lead to a relatively low decrease in the escape speed from the venturi.

Therefore, the hypersonic engine has relatively high performance within a wide range of Mach numbers. /20

There may be two setups for the hypersonic engine.

The first, with a central air-intake body, an annular combustor and a venturi limited by its "fluid" contours, has many advantages over the second setup, in which the diffuser is a reversible Laval nozzle and a nozzle with "rigid" walls.

First, in the first arrangement conditions for the start-up of the diffuser are facilitated; second, losses to drag naturally decrease due to the existence of two "fluid" walls; third, cooling of the diffuser and nozzle walls is facilitated because their surfaces are substantially smaller in the first arrangement.

As can be seen, the design of the hypersonic engine in no way differs from similar setups for usual ramjet engines, but the processes within the engines have many characteristics related to the existence of a supersonic flow in the combustion chamber.

The difficulties in designing a hypersonic engine are obvious: high engine body temperatures due to high flight speed, special arrangements for fuel distribution, flame stabilization in supersonic flow, shielding the combustor and nozzle walls from high-speed, high-temperature gases.

However, the properties of hypersonic engines are satisfactorily high. It is well known, for example, that for a hydrogen propellant the specific thrust is several times that of liquid-propellant engines. With hydrocarbon fuels it is lower than hydrogen but still substantially higher than liquid fuels (ref. 9).

The range of application for hypersonic ramjet engines is substantially broader than that of supersonic engines.

Thanks to its simplicity and relatively low cost, the hypersonic engine may find wide use in Civil Aviation aircraft (ref. 6).

Hypersonic engines may also be used for control of spacecraft on takeoff into the atmosphere and for spacecraft returning to Earth.

Recently the foreign press carried reports of the possibility of using ramjets as the second stage of ballistic missiles (refs. 9, 10, 11). This would permit using the thirty-kilometer air layer through which rockets pass, all the /21
more because the economy of the ramjet engine at these operation regimes is three or four times that of rocket engines.

The examples cited are convincing proof that the theory of the air-breathing engine created by Academician B. S. Stechkin is presently being widely developed by scientists of many countries around the world.

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N68-13570

THE FIRST EXPERIMENTAL INVESTIGATIONS OF RAMJET ENGINES BY "GIRD"

I. A. Merkulov

The theory developed by B. S. Stechkin opened the way to practical work in the creation of air-breathing engines, which began in our country. When GIRD (Group for the Study of Jet Engines) was organized, one of its teams, headed by Yu. A. Pobedonostsev, carried out the first studies of air-breathing engines. Pobedonostsev allotted several months to theoretical calculations and working out the problem of the possible areas of application of these engines. Then came the time to proceed to practical work--the study of models and individual engine components. /22

In March 1933, a test apparatus designated IU-1 was constructed for accomplishing these investigations. Its first test was on 26 March. A compressor setup designed for feeding compressed air to the receiver, from which it was to be sent to the test model, was checked out. The first official report of the tests in this new realm of technology--air-breathing engines--has come down to us. The report briefly stated:

"At 2 hrs 30 min in the morning, the switch for the electric motor setup was thrown."[1] The first test lasted fifteen minutes. Manometers showed that the air pressure beyond the fourth and last stage of the compressor reached 100 atmospheres. On the second test it reached 190 atm. Through the support of the whole GIRD group, the testing and improving of the installation progressed and after six tests it was prepared for tests of the engine model. The third group was presented the mission of the tests: "The development and investigation of the operation of an air-breathing engine with a gas fuel."

Early in the morning of 15 April 1933, the first test of the engine took place.

"The first firing of the engine completely fulfilled theoretical predictions of air-breathing engines with gas fuels. /23

"This test has initiated experimental investigations of air-breathing engines.

"Four days after the first test, the next one was carried out on the IU-1 setup. This time the engine's operation was tested for various combustion-chamber temperatures from 0 to 3.2 atm. During the test, the engine was started three times, and it was established that' in normal engine operation, ignition is required only at the start. After that, as the combustion chamber is heated, ignition can be stopped and power controlled through fuel and air supply'."

Proportional to the testing of the models of the air-breathing engine, investigation methods were gradually improved. Beginning 9 July 1933, tests on

[1] Here and later GIRD archive documents are quoted.

the IU-1 setup included measurements of the thrust generated by the test engine.

To render the engine effective not only at supersonic speeds but at subsonic as well, Pobedonostsev sought engines having air compression aided by some arrangement in addition to air compression in the diffuser resulting from the kinetic energy of the air flow. One such arrangement was the pulsejet.

To test the possibilities of creating pulsejets, an experimental valve-equipped combustion chamber designated EK-3 was set up at GIRD in June 1933.

Somewhat later that year, the idea arose at GIRD of increasing the pressure of the effect of the gas jet flowing from the liquid fuel in the diffuser. The speed of the gas escape from the liquid-fuel nozzle, as has been indicated by earlier calculations, can reach 3000 to 4000 m/sec. Therefore, if a small rocket engine were to be installed in the diffuser, the gas jet escaping from it could inject air into the combustion chamber, increasing pressure in it.

This engine design was found reasonable, but due to the great complication and difficulty of constructing it in those years, its experimental study was put off until a later time.

The 1933 GIRD tests of the pulsejet brought to light the basic problems involved in the structural development of such engines, and permitted evaluating the difficulty of their solution. In the following years it was decided to concentrate all attention on studies of ramjets. Later studies of pulsejets and injection engines were carried out at RNII (Jet Engine Research Institute) in 1936-1939.

Preparation for Flight Tests

Experimental operations in the study of ramjets were begun at GIRD in April /24
of 1933 and continued all year. Successes in the first experimental investigations made it possible to proceed to flight tests of the ramjet. Yu. A. Pobedonostsev had the bold idea of setting the engine under study in an artillery shell and performing tests at supersonic speeds, i.e., precisely the range where the ramjet engines are the most effective. The possibility of creating a ramjet engine, which still had not been constructed anywhere in the world, had to be experimentally proven. The correctness of theoretical propositions had to be proven in practice. It had to be proven that an engine of this type could actually generate thrust. In those years, when the question still existed as to whether it was generally feasible to create a ramjet engine, the only valid answer could be given by an operating engine demonstrating its ability in flight.

The choice of fuel for the engine was highly significant. As a result of careful examination of all operating parameters for the engine during the proposed tests, the following basic demands were set to its fuel: (a) it should be solid, (b) it should be easily ignited and have the property of high-speed combustion within a wide range of mixtures with air, and (c) it should have the required heating power per liter.

Having considered a large number of fuels, Pobedonostsev selected white phosphorus as one of the most suitable for the first tests.

As later progress showed, the selection proved quite fortunate. It was also decided to use a gasoline-based solid as a fuel. Therefore, the planned use of the engine in an artillery shell permitted the possible use of either phosphorus or gasoline.

In preparation for flight tests, a special portable carriage was constructed in which the engine combustion chamber was installed.

On 12 July 1933, at one of the firing grounds outside Moscow, the first tests of the phosphorus-fueled combustion chamber were held. This combustor received the designation EK-4. The aim of the first tests was to study the properties of phosphorus as a fuel for reaction engines and particularly those set in /25
artillery shells, which received the designation 08 hardware.

The tests were completely successful. In a short time--10 to 20 seconds after firing air into the combustion chamber, the phosphorus self-ignited. Combustion lasted until complete burnout of the phosphorus grain. There was no fusion or flow discharge of liquid phosphorus from the nozzle.

At the conclusion of these tests, it was stated that:

"Tests have shown that phosphorus can serve as a fuel for the second model.

"Containers for holding the phosphorus grains should be iron, as those of copper are quickly destroyed."

The aim of subsequent tests was to study the combustion of phosphorus in the combustion chamber with high flow rate of air and clarify the possibilities of using a gasoline-based solid as fuel for the 08 hardware.

During the tests, the combustor with phosphorus grains was fired twice, once with air pressure of 4 atm in the receiver and again with 1 atm pressure. Phosphorus combustion was interesting, especially in the first case. With a sharp increase in pressure in the reverser, combustion subsided briefly, after which the flame again appeared. Full burnout of the phosphorus grains took approximately 1 minute.

During these tests, firing took place with small fragments of phosphorus placed in the axial duct of the EK-4. Air pressure in the receiver was below 1 atm, so that the air consumption was relatively low. It was also decided to investigate a fuel mixture of phosphorus and gasoline-based solid.

In July 1933, powder ignition adaptations were tested repeatedly to develop a more reliable means of firing the fuel in the combustion chamber.

These tests established that powder adaptations can provide reliable ignition of fuel in the combustor. As a result, this idea of Pobedonostsev for using gunpowder for firing the fuel in the ramjet found a practical application in several versions of these engines.

In July 1933, seven tests were run, two of the VRD-1 (Air-breathing engine) and one of an engine with conic combustion chamber operating on ethylene. /26 The tests were to study carburation, ignition and combustion of the fuel-air mixture. During these tests even combustion was achieved, which showed the practicality of using not only hydrogen but hydrocarbon fuels. Twelve pounds of thrust were achieved.

All the second half of 1933 was spent preparing for flight tests of the engine.

Thanks to the solid friendly work of the small group of the third GIRD section, all test-stand studies and preparatory work opening the way to the beginning of flight tests were soon carried out. And in the autumn of 1933, the air-breathing engines underwent the world's first flight tests.

The Air-Breathing Engine in Flight

The ramjet engine designed by Yu. A. Pobedonostsev had the external conformation of a long-range 76-mm cannon shell (Standard 0124). The internal portion consisted of an intake duct, combustion chamber and nozzle. The fuel grain was located directly in the combustion chamber. Before firing from the cannon, to avoid the rupture of powder gases into the engine, the exhaust nozzle was covered with a metal block. After the engine was fired from the gun, the block separated from the shell and fell not far from the gun.

The first model of the shell also had an allowance for a payload.

The fuel grain was a metal shell filled with white phosphorus. For air to pass from the diffuser to the combustion chamber, and to aid fuel combustion, within the grain and along its axis there was a conic space set with the wide end toward the exhaust nozzle. To avoid premature self-ignition during transport and preparation for the tests, the phosphorus grains were covered by a thin film of lacquer.

The longitudinal ribs of the grain's metal case were of 2-mm sheet steel, and the transverse plates were of sheet Elektron which, it was assumed, would heat along the phosphorus and substantially raise the overall heating power of the grain.

Ten shells were set up for the tests. The testing was carried out with a /27 1902 model 76-mm gun at 20° elevation. The mean initial velocity of the shell was 588 m/sec.

Before firing the engine-equipped shells, two shots with modernized shrapnel were fired. The shrapnel fell at a distance of 7200 m. Then No. 1 shell was fired without fuel. Instead of the phosphorus grain, a grain case with sand having the same weight was set in its combustion chamber. The flight of this shell was accompanied by a strong whistle. Its flight covered 2000-3000 m. Then nine shots were taken with engine-equipped shells.

The results of these first tests corroborated the possibility of using artillery cannon for launching the engines; the test proved the full reliability of firing with shells of normal construction.

In all cases the fuel did not fail to ignite once in the combustion chamber. Igniton occurred approximately 10-15 m from the gun.

The flight tests of the air-breathing engine in September 1933 showed graphically that an engine of this type was workable. The graphic proof of this was the increase in flight distance for an engine-equipped shell (No. 3) to almost 1 km in comparison with the flight distance of a regular shell. This increase was obtained in spite of the fact that aerodynamically a missile with an open-through duct is considerably poorer than a typical shell, and consequently in the part of its trajectory where the engine was shut down the engine-equipped shell encountered more air resistance than the normal shell. In all cases, shells with operating engines flew farther than those of the same weight and shape but not powered. The sole explanation for the increase in flight distance is that the engine generated some in-flight thrust.

This fact had a great intrinsic value. The results of the flight tests not only established that the air-breathing engine functioned, but indicated the amount of thrust it generated. From preliminary calculations the force of air drag the shell experienced and the thrust force the engine generated were all determined. At flight speeds of 588 m/sec with which the missile left the cannon barrel, the calculated amount of air resistance was 20 kg, while engine /28
thrust at the same speed was 10 kg, i.e., somewhat less than the air resistance. Consequently, the engine was capable of compensating 90 percent of the air drag, but could not fully overcome it and accelerate the shell. Because drag exceeded engine thrust, the shell's speed should have decreased in proportion to the flight duration. A decrease in velocity led to still greater increase in the difference between drag and thrust. Thus, both at the moment of escape from the cannon at a determined initial velocity and in subsequent flight, the calculated engine thrust was less than the drag. This fact in no way confused investigators, because the flight tests were intended to establish the air-breathing engine's operation and determine the degree of approximation between actual thrust and calculated.

Evaluation of results showed that actual air drag exceeded the calculated, and thrust was somewhat less than calculated. This had several reasons:deformation of the metal shell of the phosphorus grain, insufficient in-flight stability, etc.

The explanation for the decrease in thrust relative to calculation and the increase in drag was a valuable result of the first series of tests. With the causes of these flaws in the engine's operation found, it remained to seek means of eliminating them in improving the engine.

After the first series, a second series was conducted in February 1934, and a third in 1935 in which six more models of the engine were planned for the 76-mm shell. Several models each incorporated several groups differing in the intake section dimensions of the diffuser or the critical nozzle throat. Some models differed in fuel supply.

The second model differed from the first only in the structure of the phosphorus grain. To decrease buckling of the longitudinal ribs in the body it was decided to allow the grain to rotate freely in the combustion chamber. With this type of construction of the grain, increase in the angular speed of the grain would not occur immediately, but gradually, which could obviate buckling in its ribs.

Thanks to improvements introduced into the construction of the engine, test results of the second model were noticeably better. The highest value for specific thrust obtained for the shell with α_{cr} = 35 mm was 320 kg/sec per kg of /29
fuel. This was 43 percent of the calculated value (750 kg · sec/kg). A decrease in the amount of specific thrust by comparison to the calculated value is explained first by the ejection of incompletely consumed phosphorus from the engine in the first moment of flight. Observation of the missile's motion permitted us to establish that when the missile left the cannon barrel, a substantial quantity of phosphorus incompletely combusted in the air fell out as a result of separation of the bottom cap. This occurred apparently because the particles of solid phosphorus fell from the shell and were scattered by the air jet from the engine as the missile left the barrel at high velocity (around 300,000 m/sec^2). Later, when positive acceleration disappeared and negative was thousands of times less due to drag, the phosphorus no longer fell from the engine because centrifugal force threw it to the combustor walls.

To eliminate fuel losses, the third model had the grain body prepared in such a way as to lessen the loss of phosphorus. In addition, phosphorus with a lower combustion temperature was used. Through improvements in the fuel grain in engines of the third model, the amount of specific thrust rose to 423 kg ·sec per kg of fuel.

In these engines, the fuel grain fulfilled its purpose of supporting the phosphorus during the launch period in the cannon and then was used as fuel. Therefore, tests of this group of missiles were quite significant. Prior to them, the interesting ideas of Tsander and Kondratyuk concerning the use of a metallic fuel in jet engines were developed only theoretically or in experimental tests on stands. The engines designed by Pobedonostsev were the world's first to operate in flight on a metallic fuel not in the form of a powder, but as a structural element.

The second group of engines of the third model was prepared with larger air scoops. The diameter of the intake section was increased to 30 mm. To test the new type of engine as fully and thoroughly as possible, shells were prepared which had not only grains with Elektron bodies, but some grains with no bodies. Here it was known that phosphorus ejected in the first moment of flight would increase substantially, but the price lowering drag, the source of which was the incompletely combusted remains of the metallic grain body, was the loss of some fuel. It was interesting to note which of the factors was more important and which shells flew farther. Engines of all three of the following models--fourth, fifth and sixth--were prepared with bodyless grains. In grains of the fourth model, the diameter of the axial duct was 15 mm, i.e., less than that of the intake section of the air scoop. In this model, the weight of the grains was increased to 645 g as against 270-300 g in earlier models. In the next two models, grains with larger-diameter ducts were used. Due to this, the weight of /30 the grains in the fifth model was decreased to 400 g.

In the sixth model the phosphorus supply was again increased, to 620 g, by placing it where the payload would be. Missiles of the fourth, fifth and sixth models reached 12 km.

Tests showed that in engines installed in shells with small dimensions it was difficult to achieve combustion with full burnout. This fact spurred construction of an engine for a six-inch shell. Such a shell with an air-breathing engine was planned and designated 14, but was not tested.

Tests had yielded a sufficiently high efficiency, reaching 16 percent at best. If we consider that a substantial portion of the fuel was dropped from the engine in the initial moment of flight, the actual amount of efficiency would be substantially greater.

The ratio of thrust to drag was approximately as follows. According to calculation data, at the moment of exit from the cannon barrel at 680 m/sec, the missile underwent drag equal to 25 kg. Engine thrust was 30 kg. In practice, at exit, drag acting on the shell with the engine shut down was 42 kg. Thrust after exit from the cannon was 23 kg. Consequently, thrust compensated for more than half the drag. With the engine functioning (in spite of the force of gravity), the braking force of air drag was not 42 kg but only 19 kg. Due to this, flight distance was increased.

A concise recapitulation of the results of the first tests with ramjet engines shows that even early in the development of rocket technology, with very /31 limited experimental capabilities, scientists strove to study the operation of this new type of engine more widely and to grasp the principles controlling the processes operating in them.

The decisive result of these tests accomplished by success begun in GIRD's work on air-breathing engines was the experimental proof of the workability of these engines. The basic question--would the ramjet engine operate--received a clear answer: yes, the ramjet engine, created on the basis of B. S. Stechkin's theory, was capable of operating in flight and generating thrust. This was the important conclusion.

One more fact of historical importance must be noted. The ramjet engines of Yu. A. Pobedonostsev's design were the first jet engines which broke into the supersonic range. The shell with the air-breathing engine operated at a speed double that of sound. No rocket in the world had previously attained such a speed.

Flight tests of shells with ramjet engines were conducted by a group headed by Yu. A. Pobedonstsev which included: M. S. Kisenko, A. G. Salikov, A. N. Ryazankin, G. V. Shibalov, I. A. Merkulov, L. E. Bryukker and O. S. Oganesov.

Because experiments supported the idea that such engines could function, the theoretical conclusions of B. S. Stechkin and F. A. Tsander and foreign scientists including especially the Italian Academician Crocco concerning the expediency and great effectiveness of ramjet engines on various aircraft were consequently considered well-founded.

Now a second challenge--solving the problem of the practical use of ramjets on aircraft with scientific or defense purposes--loomed before the scientists.

The investigations carried out, while proving the workability of the air-breathing engine, at the same time showed that these engines generate relatively little thrust. In the first tests of the engines in shells, their thrust did not reach the amount of the drag on the shells tested.

Naturally the question arose as to whether the ramjet engine could generate thrust exceeding drag experienced by the engine encased in a streamlined nacelle. This remained to be solved in the next stage of investigations. /32

N68-13571

FIRING OF THE WORLD'S FIRST RAMJET ROCKET

V. P. Kaznevskiy

The flight tests of a supersonic ramjets designed by Yu. A. Pobedonostsev proved in practice that this type of engine generates a reactive force through which the flight distance of a ramjet-equipped shell was significantly greater than that of a regular shell. /33

Having proven the workability of the engine, the investigations also showed that these engines generate relatively little thrust, and in turn questioned the possibility of creating a ramjet generating thrust greater than the drag experienced by an engine body housed in a streamlined nacelle.

To solve this question the engineer I. A. Merkulov studied the ramjet thermodynamic cycle and for his first conclusion established that the ramjet engine operating according to the Brayton cycle, i.e., with combustion for p = const, cannot generate thrust greatly exceeding the drag it experiences, i.e., cannot in practice even to push itself, much less communicate acceleration to any type of aircraft. This arises because air in the combustion chamber of the ramjet must be heated to a high temperature to obtain the most thrust possible. However, while raising the gas temperature, maintaining constant pressure requires increasing the area of the cross section of the combustion chamber proportional to the increase in temperature. Therefore, with an increase in thrust the dimensions also increase, and consequently so does the amount of engine drag.

However, this negative conclusion did not hold back further tests of the ramjet. It was established that if we were to proceed on the basis of decreasing the thermal efficiency of the cycle, achieving fuel combustion at decreased pressure, it might be possible while losing some thrust to substantially reduce the engine dimensions and consequently decrease drag. Naturally, the question arose /34
as to how much the radial dimensions of the ramjet combustion chamber could be decreased.

It was necessary to select engine dimensions for which the free thrust, i.e., the difference between engine thrust and drag, would be greatest.

From the analysis of the heat cycles of the air-breathing engine, Merkulov selected the optimal engine parameters at which it could generate thrust significantly exceeding its drag. On the basis of these theoretical investigations, in 1936 he and a group of workers from the Jet Department on the Ts. S. Osoaviakhim Stratospheric Committee planned test models of the air-breathing engine. A. F. Nistratov, O. S. Oganesov, B. R. Pastukhovskiy, L. E. Bryukker, M. A. Merkulova, B. I. Romanenko, L. K. Bayev and others took part in the development of these engines. A large number of calculations for the theoretical investigations of the ramjet cycle were done by A. D. Merkulova.

Now the effectiveness of the engine's operation had to be verified in practice, in test flights, and the engine had to be proven capable of accelerating an aircraft in which it was installed. It was decided to run the first tests on rockets. Therefore, the designers planned a rocket with a ramjet engine installed in the body. In the upper part of the rocket body, between the diffuser walls and the nacelle, a space was set aside for a parachute and payload.

The ramjet-powered rocket naturally might be tested only as a second stage rocket, while for the first stage some other type engine-equipped rocket such as liquid- or powder-propellant rocket might be required. For simplicity and reliability, it was advisable to use a powder-propellant rocket as first stage. Thus, a two-stage rocket was designed in which the first stage was a powder-propellant rocket and the second was an air-breathing rocket. All the GIRD tests were used in this design. As in the engines of Pobedonostsev, the air-breathing engine for the rockets used a solid propellant set in the combustion chamber as a grain.

The rocket design was completely examined by many scientists, who both approved it and supported the group working on it. It is interesting to acquaint ourselves with the conclusions of our scientists of a quarter century ago. Here is one: /35

"Conclusion concerning comrade Merkulov's draft plan 'A Rocket With an Air-breathing Engine.'

"Having acquainted myself with the proposed draft plan, I find it of great interest.

"1. This is the first use of an air-breathing engine for stratospheric rockets. Preliminary calculations permit concluding that the engine offers a significant advantage over the usual type of rocket engines for atmospheric flights.

"2. The firing method selected is the simplest and cheapest, both providing the required speed (to 300 m/sec) and permitting the assumption that the rocket will be stable in flight.

"3. The author's data are based on experimental (efficiency) data.

"4. I point out especially that the proposed plan is completely feasible in that the basic moments, namely (1) the operation of the powder-propellants engines selected for firing, and (2) the engine operation on several propellants proposed by the plan were successfuly tested in practice. The draft plan developed by comrade Merkulov and the explanatory notes presented are sufficient to begin practical operation (finishing the planned project and beginning operations).

"In summary, I feel that the plan is quite feasible.

"Engineer Zuyev[1]"

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[1] Documents quoted in this article are presently in the Scientific Archives of the Institute of History, Natural Science and Technology of the USSR Academy of Sciences.

Professor V. P. Vetchinkin, who regarded the plan for air-breathing rockets highly, wrote in his report of 18 January 1938:

"The main issue in question, in my opinion, has been very well resolved: by decreasing the area of the largest (third) cross section by several times compared to the theoretical , which was chosen for constant pressure in the combustion chamber, the author achieves his object of creating thrust stronger than drag, i.e., the engine's capability to fly independently. The essence of the plan was to resolve this.

"The simplest performance has been prposed for the first model--a rocket flying vertically, which is easily tracked.

"The calculated flight altitude is 26 km, which has nto yet been attained by powder- or liquid-propelled rockets, even in calculations.

"The simple design promises cheap construction.

"It is absolutely necessary to construct several test models of the rocket of the proposed type and test them first on the ground and then in flight."

Professor K. A. Putilov carefully examined, tested and approved the thermodynamic calculations for the air-breathing engine and sanctioned work on creating rockets with such engines. Professor K. L. Bayev, who warmly supported the work /36 of the young engineers, greatly aided completion of ballistic calculations.

The support of outstanding scientists and leading specialists in the realm of rocket technology for the plan opened the way to realizing this plan. At one of the aviation factories, in the Special Design Department directed by A. D. Shcherbakov, work began in 1937 on the creation of air-breathing rockets. First, two engine models were planned which were intended to systematically investigate the processes occurring in air-breathing engines. To more quickly solve the basic problem of proving the feasibility of creating an air-breathing engine which would generate thrust exceeding drag and could propel an aircraft, a rocket designated the R-3 was planned. Solid grains consisting of a mixture of aluminum and magnesium powder with some additives were selected as propellant. Cylindrical grains with an open-through duct in the center were installed in the combustion chamber. Two types of propellant grains were set in the rockets. One, prepared by the Moscow State University (MGU) chemist V. A. Abramov, consisted of powdered aluminum and magnesium fixed by an organic filler. These grains were quite stable and were uniformly burned in the combustion chamber. The heating efficiency of the fuel comprising the grains was 4200 kcal/kg. The rocket's heat charge consisted of two grains with equal external diameter but with different diameters of the internal duct through which air passed from the engine diffuser to the combustion chamber.

Fuel consumption was aided by gunpowder ignited by a blasting fuze. Total weight of the propellant grain was 2.1 kg, and combustion time was 8 sec.

Other type grains were prepared in the D. I. Mendeleyev Chemical Engineering Institute in Moscow under the direction of Abramov's scientific co-worker Dergunov. They found a means to compress aluminium and magnesium powders under high pressure. To intensify the combustion process and increase engine thrust, a certain amount of oxidizer (potassium chlorate) was added to these grains.

Tests of the R-3 were conducted by a team consisting of engineer I. A. Merkulov, mechanics P. V. Karev and I. A. Charnyy, engine operator V. N. Akatov and chemist V. A. Abramov.

For flight tests, three series of rockets totaling 16 in number were prepared. /37

The technical data of the rockets (first series) are: weight of powder-propellant rocket--3.8 kg, weight of powder--1.4 kg, full impulse--260 kg/sec, maximum thrust--450 kg, average thrust--118 kg, combustion time for powder--2.24 sec, weight of engine-equipped rocket--4.5 kg, diameter of engine-equipped rocket--121 mm, full initial weight of two-stage rocket 8.3 kg.

Later models of the R-3 differed from those of the first series by some lightening in construction.

The first stage in tests of the R-3-2v were powder-propellant rockets with the following characteristics: full rocket weight--3510 kg, weight of powder--1050 to 1079 kg, gas escape velocity--1860 m/sec.

The first stage of the experimental operations was the aerodynamic testing of the rocket in a wind tunnel. In 1938 and early 1939 several dozen tests were run. Through these, the rocket's drag coefficients, the speed braking for powder-propellant rockets intended for the fastest release of the first stage from the second were determined.

Simultaneously, combustion tests in the combustion chamber were being carried out.

In February of 1939, flight tests of the engine were initiated at the airfield near the Planernaya station. The rocket was launched from a vertical launcher. The first tests dealt with launching, stage separation, and fuel combustion. The first successful flight clearly establishing the increase of rocket speed attributable to the operation of the air-breathing engine took place on 5 March 1939.

In two months--in the first days of May--tests took place presided over by the chief of the Special Design Department A. Ya. Shcherbakov, leaders of the invention factory V. V. Kol'tsov and P. M. Blayman, representative of the Zavkom (factory committee) S. M. Kumanin and others.

In two rockets tested that day, the propellant grains prepared by V. A. Abramov were tested. These tests clearly showed the reliability of all systems. It was decided to carry out official tests with the representatives of the aviation industry Narkomat (people's commissiariat). For accurate determination of flight speed and lift altitude of the rockets, a team of astronomers headed by V. A. Bronshten was invited, and accomplished their task by using meteorite observation methods. /38

Official tests began 19 May 1939. Night was chosen so as to determine the rocket's movement through tracking the gases escaping from the engine against the background of the dark sky. A propellant grain prepared in the Mendeleyev Institute was installed in the rocket. After shutdown of ignition of the powder, the rocket flew from the launcher and rose. After separation of the first stage, the engine-equipped rocket clearly gained altitude. The rocket's successful flight was clearly apparent to those attending the test.

Data reduction by the team of astronomers established the following sample picture of the flight:

During firing of the first stage, the rocket reached a speed of 200 m/sec and a height of 250 m. After burnout of all its propellant, the first stage separated by an air brake installed in it. From the moment when the powder stopped burning until firing of the engine there was a lapse of about 2.5 sec. During this time, the rocket advanced 375 m, rising to an altitude of 625 m. The rocket's speed until this instant had been increased to 105 m/sec. At this flight speed, the ramjet engine was fired and operated 5.12 sec. Toward the end of the engine's operation, the rocket rose to 1317 m, reaching a speed of 224 m/sec. After burnout of the propellant, the rocket flew 6.06 sec on momentum and rose to 1808 m. By the end of engine operation, excess thrust, i.e., the difference between thrust and drag reached 20 kg, and the thrust coefficient was 0.7. Throughout the entire flight period with engines operating, the average speed was 23 m/sec^2.

Test results of these, the world's first ramjet-propelled rockets, were established by a report which fully describes them. Let us explain that at that time terminology in the literature was not firmly established and the engines installed in rockets were called air-rocket engines and the rockets themselves, keeping in mind their use not only for altitude studies but defense purposes as well, were called wingless torpedoes.

"Report on the tests of the air-rocket engine.

"On 19 May 1939, at the airfield of Planernaya station (outside Moscow), the tests of the air-rocket engine designed by I. A. Merkulov took place. /39

"The object of the test was a wingless torpedo with an air-rocket engine.

"The engine's fuel composition was prepared at the Mendeleyev Chemical Institute.

"A normal powder-charge rocket was used for firing the torpedo.

"Ignition of the fuel and combustion of the powder-propellant rocket took place with the aid of an electrical fuse powered by a battery. A blasting fuze was introduced between the fuel and the electrical fuse to delay ignition of the mixture one second with respect to the fuse of the powder-propellant rocket.

The torpedo's flight altitude and speed were determined by a team of astronomers.

"The torpedo was mounted in a launch for firing.

"Firing took place at 22 hr 40 min. The torpedo's tests yielded these results:

"The torpedo flew vertically from the launcher. After 1 second, the powder-propellant rocket separated from the torpedo through a built-in air brake and fell below. At this instant the air-rocket engine began to operate. Behind the exhaust nozzle of the engine a trail of glowing combustion products formed vertically below. The engine operated evenly and continuously. The duration of engine operation in relation to the amount of fuel consumed was 5.5 sec. The beginning of engine operation introduced a strong increase in flight speed. With increased speed, the torpedo continued upward throughout the period of the engine's operation. After exhaustion of all fuel, the torpedo continued flight on momentum. The whole flight was stable and strictly vertical.

"The flight of the rocket has fully substantiated the reliable operation of the air-rocket engine and the increase in flight speed during its operation."

The tests of the rocket quite clearly demonstrated the rapid vertical flight of an aircraft with a ramjet engine.

These tests proved in practice the possibility of creating a ramjet engine capable of generating thrust exceeding drag and even the combination of drag and weight.

Thus ended the first stage of the work of Soviet scientists and designers in the creation of ramjet engines.

FLIGHT TESTS OF THE RAMJET ON AIRCRAFT
DESIGNED BY N. N. POLIKARPOV
IN 1939-1940

A. Ya. Shcherbakov

In the 1930s, work in rocket technology and the conquest of the stratosphere /40 was gaining momentum. Several stratospheric balloons were flown to altitudes of 22 km. In Leningrad in 1934, there was an all-union conference on the study of the stratosphere at the instigation of the USSR Academy of Sciences. The first successful flights of Soviet rockets with liquid-propellant engines were in 1933; 1934 saw the initiation of the work by the Jet Engine Research Institute created on the basis of GDL and GIRD. The first scientific and engineering conference on rocket technology was held in Moscow in 1935.

Scientific research and experimental design work broadened and was aimed at creating a stratospheric aircraft. In 1935, we introduced into the plan of these operations the proposition of launching a high-altitude towed glider, which in principle permitted piloted flights into the stratosphere to altitudes of 30 km and more.

To accomplish this, a Special Design Department (OSK) was organized at the Aviakhim factory where practical works and actual experiments were begun. Included in the tasks to be solved in attaining high altitudes and flight speeds were the problems of designing sealed cabins, jet engines, methods for carrying out such flights, etc.

Well-known specialists and designers were invited to OSK to partake in accomplishing these missions. They included the engineer I. A. Merkulov, with his experience and knowledge in the creation of reaction engines. It was first proposed that OSK would build an experimental aircraft with ramjet engine. This aircraft might be similar to the high-altitude towed glider we developed, then unhook from the towing system, switch to gliding and generate the high speed suitable for the operation of the ramjet. After ignition of the engine, the /41 craft could fly independently, building up flight speed and altitude.

Engineer Merkulov was charged with completing the aerodynamic calculations and development of the design sketches of the ramjet-driven experimental aircraft. Simultaneous with the successful completion of these works, he designed two ramjet models for test-stand study as well as ramjet rockets which were flight-tested in March-May of 1939.

After the successful tests of the ramjet rockets, the Aviakhim factory OSK decided to direct future efforts toward the creation of an aviation ramjet for installation in an aircraft.

On 3 July 1939, at a conference of the NKAP (Aviation Industry People's Commissariat) Engineering Soviet, Merkulov presented a report on the results of experiments with ramjets on rockets and on the tasks of future study of the air-breathing engine, and improvement of its construction and its uses in aviation.

He proposed the use of ramjets in propeller-driven aircraft. The ramjets could be used as auxiliary motors for increasing maximum flight speed. At that time, the propeller was the only power setup in practical use for aircraft. It gave the craft high economy in takeoff and cruising and good maneuverability in the air. At the same time a light ramjet might offer the pilot greatly increased maximum flight speed when necessary. The suitability of the jet as an auxiliary motor was due also to the fact that it required no special fuel supply, which would be necessary, for example with liquid-propellant rocket engines, and it could be supplied the same gasoline as the main motor.

In August of 1939, the first models of the aviation ramjet--auxiliary to the DM-1 motor for use in ground tests--were designed and built. The diameter of these engines was 240 mm. Their test-stand were performed in September of 1939. The character and content of the tests are put forth in reports compiled from the results. Here is one:

"Report on the Tests of the air-breathing engine.

"On 17 September 1939, tests were performed with the air-breathing engine at the Planetarnaya station airfield.

"The tests were to prove the engine's reliability during extended operation and the engine was operated continuously up to 30 minutes.

"The tests were conducted on an engine with duralumin fairing and frames. Ignition was by two sparkplugs. /42

"To test the safety of the plugs, two others were installed at other points in the engine.

"At 15 hr 26 min the engine was fired and operated without missing until 15 hr 57 min, when the fuel cock and air cock were closed.

"Thus, the engine operated 31 minutes. After the test, the engine's operation was checked. The engine appeared to be in completely good condition and the plugs were undamaged.

"Thus, the test established the complete reliability of the engine in continuous operation for one half hour.

"ORPI chief: Kol'tsov, Engine designer: Merkulov.

"Factory engineer: Maslov Factory flight mechanic: Karev"[1]

The successful tests of the DM-1 permitted proceeding to the preparation of engines for installation in aircraft. In September 1939, three models of the

[1] "A Concise Account of the Tests of the Air-Rocket Engine for Increasing Maximum Flight Speed," page 73. Scientific Archives of the Institute of History of Natural Sciences and Technology, USSR Academy of Sciences.

DM-2 auxiliary motors were prepared.

The auxiliary motor combustion chamber, unable to accomplish complete combustion, was aided by a special cooling system in which gasoline entering the engine was used as a coolant. The stability of gasoline combustion in the combustion chamber was achieved by a special structure, the so-called auxiliary rings, set within the combustor. They created a zone in the combustor where there were low airflow speeds and in these protected zones--the mixing chambers --there was ignition and stable combustion of a small amount of gasoline. The flame leaving the rings aided combustion distribution throughout the air mixture. To obtain ignition within the temperature limits -60° to +60°C andthe possibilities for multiple starting in flight at various velocities, a special electrical ignition instrument was created and used in several flights.

The DM-2 engines were quite compact. Their length was 1500 mm, and maximum diameter was 400 mm, diameter of the nozzle exhaust section was 300 mm, engine weight was 12 kg without motors and 19 kg with motors.

To study the operation of ramjet engines before flight tests, a special wind tunnel AT-1 was constructed. (After improvement it was designated AT-2.) The maximum speed of the air flow in its working section was 75 m/sec. Tests of the auxiliary motors, first in the AT-1 and then in the AT-2, proved the safety of the engine operation, ignition, and the stability of the combustion and determined the engine's parameters. These tests were conducted throughout the period of flight tests of the auxiliary motors (DM) both with the aim of checking the /43 structural improvements introduced during flight tests and for periodic control of the operation and condition of the engine itself.

Tests of two DM-2 models were initiated in October of 1939.

On 22 October 1939, official tests of the DM-2 took place in the wind tunnel. The results of these tests are given in the report, where it was stated:

"On 22 October 1939, tests of the air-rocket engine constructed by I. A. Merkulov were performed at the Frunze Central Airfield.

"The tests were witnessed by Central Committee Factory partorg (Party Organizer) G. V. Odinokov, factory director P. A. Voronik, and chief engineer P. V. Dement'-yev. The tests took place in a special wind tunnel.

"The air-breathing engine operated on regular aviation gasoline with an ethyl liquid. Control of the engines was accomplished through handles on a control panel which controlled the supply of gasoline and buttons sending an electric flow to the engine sparkplugs.

"The amount of engine thrust was determined by single-component weight.

"During the tests, the engine was fired three times. The control components worked flawlessly. The engine showed complete reliability and safety from explosion.

"A speed of 120 km/hr was attained. At a given speed, the engine developed 10 kg of thrust, which corresponded to calculations."[1]

Ramjet Engines in the I-15a Aircraft

After successful tests of the air-breathing engines in wind tunnels, they were installed for flight tests in the I-15a (I-152) No. 5942 designed by N. N. Polikarpov.

In the first tests, the aircraft in which they were installed was for all practical purposes a flying laboratory for testing the ramjet engine operation.

To shield the fuselage and tail structure from the possible harmful effects of engine combustion products, they were covered with sheet duraloy.

Flight tests of the I-15a with two ramjet engines set under the aircraft's surfaces as auxiliary motors began December 1939. Tests of the first aircraft were by test pilot Petr Yermolayevich Loginov. /44

The first five flights were to check improvements on the machine. Then flights tested ignition in the air, and the engine's ignition. These first flights achieved reliable ignition and stable operation of the ramjet engine.

The official tests of the I-15a with ramjet engines were held on 25 January 1940. In accordance with his assignment, P. Ye. Loginov piloted the craft through several loops over the Frunze Central Airfield with the ramjet engines operating. During this flight, the pilot shut down and reignited the auxiliary motors several times. The engines' operation proved to be reliable, stable and safe for flight. Even when the pilot fed the auxiliary motors their maximum fuel load, during which the jet leaving the nozzle was longer than the fuselage, the craft banked well and the pilot controlled the craft easily, demonstrating its complete safety.

The flights by Loginov in December 1939 and January 1940 were the world's first flights of an aircraft equipped with air-breathing engines. It is interesting to note that the first flight of a foreign aircraft with air-breathing engine built by the Italian firm Caproni, which was widely publicized by the foreign press, occurred only in August of 1940, i.e., seven months after the flight of the Soviet I-15a aircraft with air-breathing engines.

Tests of the engines on the I-15a continued through February, March and May of 1940. These flights were to test the various structural improvements aimed at shortening ignition time, improving combustion and increasing the engines' effectiveness. Then flights were performed to measure the increase in speed due to the auxiliary motors. In these flights, in addition to Loginov, there were test pilots A. V. Davydov and N. A. Sopotsko. Flights on the I-15a aircraft with the DM-2 totalled 54. Of these, Loginov made 34, Davydov made 18, and Sopotsko made two flights. The craft's velocity with the ramjet operating /45

[1] Op. cit., page 74.

increased by an average 18-20 km/hr. The tests were at 320-340 km/hr. The auxiliary motors in these flights developed approximately 100 hp. A clearer indication of the flight results is given in the table. /45

It must naturally be kept in mind that as engine weight increased, flight speed decreased somewhat, and the true increase in speed was less than the amounts indicated. However, in using an aircraft as a flying laboratory, the minor decrease in its velocity had no great significance, while in practical use of the ramjet, it has been proposed to substantially decrease drag through good fairing or even introducing additional motors in the craft's construction. This was being developed even during the flight tests.

RESULTS OF TESTS OF THE I-152-DM AIRCRAFT[1]

	1940					
Flight date	27 Feb	10 Mar	11 May	9 Jun	19 Jun	20 Jun
Altitude	2000	1250	2000	3200	1000	2000
Speed (km/hr)	311	301	304.5	317	302	313
Speed increase (km/hr)	21	17.0	22.0	19.5	18.0	18.0

The test pilots who performed the flights on the craft equipped with air-breathing engines voiced opinions of them, one of which we present here:

"Conclusion of pilot Loginov concerning the operation of the reaction engines designed by I. A. Merkulov.

"1. The engines give the I-152 aircraft an appreciable increase in speed.

"2. Control of the engines' operation is easy and simple (one control stick with switch).

"3. Engine operation at all speeds is stable and safe in terms of fireproofing when the craft's lower surface is shielded with a protective sheet of metal.

"4. The time required for starting the engine is somewhat long, 40-50 sec. This period should be shortened to 5-10 sec.

"5. The engines did not undergo complicated flight maneuvers.

"Test pilot Loginov.
"10 July 1940"

A special commission appointed by order of the Narkom (Peoples' Committee) compiled the following report: /46

"Report concerning tests of the I-15a aircraft with air-breathing motors.

"On the basis of flight-test results, the commission states that workers of

1 Op. cit., page 66.

the Aviakhim factory have created an air-breathing engine which operates in an aircraft and increases flight speed.

"The engine's safety, fire-resistance and durability have been proved by prolonged ground and flight tests.

"The tests have established that the air-breathing engines increase the craft's speed of 315 km/hr by 15 km/hr.

"The commission feels it worthy to continue tests on the high-speed engines, as they are the most effective air-breathing engines. At the same time, the Commission feels it necessary to continue work on the engines with the intention of increasing their efficiency, improving ignition, and accurately determining fuel required.

"Commission president Shumovskiy, chief military representative of the Frantsev. factory.
"Invention division chief Blayman.
"Designer Merkulov"[1]

The Ramjet Engine in the "Chayka" Aircraft

After the tests of the I-152-DM aircraft, tests of air-breathing engines were performed on the well-known "Chayka" I-153 aircraft designed by N. N. Polikarpov. Tests were performed on the I-153 craft No. 6034. Flight tests of the I-153 with DM-2 were begun in September 1940. They were performed by test pilots P. Ye. Loginov, A. I. Zhukov and A. V. Davydov. The average speed increase of the Chayka with operating DM was 30 km/hr. The table gives flight results.

RESULTS OF TESTS OF THE I-153-DM AIRCRAFT[2]

		1940	
Flight date	3 Sep	12 Sep	20 Sep
Altitude (m)	2000	2000	2000
Speed, (km/hr)	385	385	388
Speed increase (km/hr)	29	33	27

In August 1940, new DM-4 air-breathing engines were prepared which differed from the DM-2 by their larger dimensions. Construction of the DM-4 was an outgrowth of the construction of the DM-2. /47

The first flight of the I-153 with DM-4 auxiliary motors took place on 3 October 1940. The aircraft rose to a height of 2000 meters and at an absolute speed of 388 km/hr, thanks to the ramjet engine, speed was increased by 42 km/hr, making it 430 km/hr. During later flights with DM-4 engines, the average increase

1 Op. cit., pages 3-4.

2 Op. cit., p. 69.

in speed was approximately 40 km/hr in comparison with flight without such engines. An increase from 389 km/hr to 440 km/hr, i.e., of 51 km/hr was obtained on 27 October 1940 in the I-153 with DM-4 engines at 2000 meters.

From the results of flight tests of the I-153 with DM, a report was prepared in which it was stated:

"In October 1940, the invention section of the factory performed flight tests of the I-153 aircraft with air-breathing engines designed by I. A. Merkulov. The engines were installed in the aircraft as auxiliary motors under the craft's lower surfaces and fastened to existing bomb girders. The two auxiliary motors weighed 60 kg.

"Fuel supply for the engines was from gasoline tanks on the craft which simultaneously fed the M-62 motor. The engines were controlled through a stick in the cabin.

"The I-153 was tested by Loginov at the Frunze Central Airfield. The program consisted of 20 flights providing a check of the craft's stability with the auxiliary motors, tests of their operation and determination of the increase in maximum speed.

"The flight tests completely established the effective operation of air-breathing engines and through their operation an increase in maximum flight speed.

"Tests showed these engines capable of operating on any type of aviation gasoline regardless of the proportion of ethyl.

"The engine's durability has been proved in prolonged ground and flight tests. Flight tests have established that firing the engines on the I-153 flying at an altitude of 2000 m increases its top speed from 389 km/hr to 440 km/hr, i.e., by 51 km/hr."[1]

Flight test results received a positive evaluation in the Narkom aviation industry Order No. 391 of 16 December 1940.

The tests permitted both basic debugging of the engines and further R and D work in improving them. As the tests clearly showed, these problems included studying combustion in the ramjet combustor and improving it to attain full combustion, improving the ignition system and improving construction of the ramjet with respect to its further simplification, as well as equipping the engines with control/measurement equipment and automation. /48

"Tests of aircraft with both DM-2 and DM-4 air-breathing engines totalled 74 flights with no accidents.

Work in planning and flight tests of the ramjet on aircraft designed by N. N. Polikarpov was initiated in the special construction section under the direction of A. Ya. Shcherbakov and continued in the invention section directed

1 Op. cit., pp. 5-6.

by V. V. Kol'tsov and P. M. Blayman of the Aviakhim factory. It was accomplished by the design group, which included designers I. A. Merkulov, A. P. Masolov, A. A. Mel'nikov and B. A. Nikolayveskiy, engineers A. A. Gonsovskaya and Z. V. Tolstikova, aviation mechanics I. A. Charnyy, P. V. Karev and A. N. Il'in and G. P. Rybokov.

Simultaneously with the ramjet engine tests described here, our group performed successful work in high-altitude stratospheric flights as well.

By the end of 1940, these works accomplished the creation of several air-tight cabins in which flights above 12 km were accomplished.

Such a cabin underwent government testing in the I-153 at the Air Force Research Institute and was recommended for installation in several fighter aircraft.

This success in creating air-tight cabins, high-altitude flights on gliders mentioned in the Soviet and foreign press and successful tests of ramjet engines served as a basis for solving the important question raised by the Central Committee of the All-Union Communist (Bolshevik) Party and the USSR Soviet of Peoples' Commissars concerning the organization of a test factory at which work might be continued in attaining high-speed altitude flights.

The factory began organizing in the second quarter of 1941 in unsuitable /49 quarters and just as it began to produce, World War Two began and curtailed the continuance of work in this field on the scope and scale intended.

EXPERIMENTAL PREPARATION FOR FLIGHT TESTS OF THE RAMJET ENGINE IN AN AIRCRAFT DESIGNED BY A. S. YAKOVLEV IN 1942-1944

K. A. Putilov

In all our affairs, the most impartially strict judge is time. After a quarter century has passed and we glance back, we realize that much of what we scientists and technicians have done was incorrect or immaterial and suddenly little appears historically important. Today we recall with great interest one of these useful items--the creation of the theory of air-breathing engines and the first researches and investigations with ramjet engines to support this theory experimentally. /50

Before the War, in 1939 and 1940, and during the War, we in the USSR had been studying ramjet engines in several laboratories and groups directed by V. S. Zuyev, Ye. S. Shchetinkov, M. M. Bondaryuk and I. A. Merkulov.

I can speak only of the work in which I took some part--that of the special design office directed by Igor Alekseyevich Merkulov.

What challenge faced us in those years?

There was the theory of the air-breathing engine put forth by Boris Sergeyevich Stechkin and developed by his students and successors, among whom Moris Rua is well remembered. There were the results of the first experimental studies of the ramjet engine performed in 1933-1935 by Yu. A. Pobedonostsev in GIRD and RNII, and in 1935 by Rene Leduc in France. There were the highly valuable results of that era's most complete laboratory studies of the ramjet engine combustion processes by V. S. Zuyev in 1937-1940 and the flight-test results of the ramjet engine in rockets and aircraft as well as in the TsAGI (Zhukovskiy Central Aerohydrodynamic Institute) T-104 wind tunnel accomplished by I. A. Merkulov in 1939-1941. However, these data alone could not offer complete experimental proof of the theory and calculation methods of the ramjet engines for designing high-power ramjet engines. /51

Therefore, the most immediate problem was to design satisfactorily performing models of the ramjet engine and test them initially on the ground, but under conditions more-or-less approximating those of flight, and then necessarily flight-test them.

Such firing tests of aircraft ramjet engines, some of the world's first in their thoroughness, were prepared and performed by a special design office and the Ordzhonikidze Aviation Institute in Moscow.

It must be stated that in those years few were willing to share the enthusiasm in rocket technology, because this field then appeared exotic and diverging from the pressing needs of aviation. We were fortunate that the Director of MAI (Sergo Ordzhonikidze Moscow Order-of-Lenin Aviation Institute) then was Aleksandr Ivanovich Mikhaylov. At his own risk, to aid the SKB (Special Design Office), he established the Special Experimental Investigation Group (SEIG) and the theme "Further Improvement and Testing of Special Types of Auxiliary Motors."

With the concurrence of A. I. Mikhaylov and his assistant Professor Nikolay Viktorovich Inozemtsev, we succeeded in surmounting the various and often complex obstacles arising from the difficulties of the war years.

In 1942, the engineers and technicians of the SKB and their co-workers from SEIG MAI designed a steel wind tunnel with a length of 17 m and a working section diameter of 1 m. The speed of the airflow in the tunnel's working section was around 50 m/sec. The tunnel was equipped with measurement apparatus for simultaneous measurements of twenty-two parameters: temperature, speed and pressure at various points of the ramjet.

Due to the war, Merkulov set up the design models of the ramjet far from Moscow, and they were flown to Moscow for tests and further improvements.

V. I. Bukharin, N. I. Zaikin, D. N. Chekletov, O. S. Oganesov and others took part in the structural development of the engines. The engineer B. A. Nikolayevskiy planned the engine's installation in the aircraft, the fuel supply system, electrical supply and control. In-operation blowdown in the tunnel was conducted by B. A. Nikolayevskiy, B. R. Pastukhovskiy, I. A. Charnyy and Ye. A. Asadchikov. In Moscow, the spirit of the operations, the organizer of tests and initiator of various improvements was the indefatigable inventor, the partorg (party organizer) of the MAI department of Physics, Boris Rafailovich Pastukhovskiy. I have never met a more enthusiastic supporter of jet technology. Alas, a few years after this period described, nervous overstrain due to such work /52
ended the life of this remarkable man. We will always revere his memory.

Many unforeseen difficulties arose during operational tests of the ramjet engine. Department members P. V. Matorin and S. A. Lapushkin aided in solving some of them.

What had to be studied first in ground tests? First, the conditions for sufficiently complete fuel combustion and pressure change throughout the gas-air duct of the engine, i.e. those processes which affect the speed of gas flow from the nozzle. It was of course necessary to test and develop the ignition reliability, combustion stability and the fire-resistance of all of the engine's structural components.

To arrive at a solution to these questions, flow velocities were measured at the intake, at the exhaust and in the working section. Static pressure was measured along the engine axis in front of the diffuser, at several points in the diffuser and in the combustor. Air temperature after compression in the diffuser was measured, as were the temperature in the combustor and in the exhaust section of the nozzle along the axis and near the walls. These data permitted calculation of all the processes with sufficient accuracy. Flight tests on aircraft designed by N. N. Polikarpov showed both the positive features of these engines: safety, durability, ability to operate on any type of aviation gasoline, stability of the combustion process, and fair reliability of the ignition system, as well as their faults, chief of which was incomplete combustion.

Therefore, immediately after completion of the flight tests, in 1941 tests of the DM-4 engine were run in the TsAGI T-104 wind tunnel and revealed the causes of low combustion. Thus, several changes were introduced into the new DM-4s engines to be used in tests on an aircraft designed by A. S. Yakovleva (the YaK 7) to increase the completion of combustion and decrease pressure losses. In addition, the DM-4s incorporated detachable diffusers and nozzles of various dimensions, for selection of optimal geometrical parameters for the engine during tests. In addition to the basic version of the diffuser, one was designed with an injector in which vaporous gasoline served as the fuel. The protective rings installed in the combustion chamber also had several designs.

Because tests in the T-104 tunnel showed that the peripheral fuel supply does not yield a uniform gasoline mixture, the new engines had annular burners throughout the section of the combustion chamber. These had various structures for flame stabilization. Ignition in the auxiliary motors was started by the ZPz-DM-5 device powered by a 12-A-30 battery. The circuit feeding power to the ignition device was tied in to the AZ-DM-1 automatic device, which automatically broke the circuit after the engines started. If the engines were to die, as a result of a prolonged lapse in fuel supply for example, the AZ-DM-1 would start the flow to the combustor. The DM-4s had a diameter of 500 mm and a length of 2430 mm. /53

The three removable diffusers had intake sections of 230, 280 and 330 mm. The removable nozzles had intake diameters of 300, 340 and 360 mm.

Tests in the AT-2 tunnel began in mid-August of 1942. The first step was to test the engines in operation after their production, adjust and check the whole complex in operation and debug especially the fuel flow in the welded seams and the connecting pipes and gas flow at points where the removable attachments met the body. Much attention was paid to tests and corrections of the ignition system in the auxiliary motors. At the same time, the measurement device reinstalled in the tunnel was tested. The nature of the first tests is clearly illustrated in reports from that time, one of which we present here:

REPORT NO. 1

This report has been prepared by the Commission consisting of: Chief of test Station I. A. Charnyy, chief test station engineer Ye. A. Asadchikov and engineer B. A. Nikolayevskiy to state that DM-4s engine No. 14 was installed in the AT-2 wind tunnel on 17 August 1942 for testing ignition and combustion.

After the first fuel combustion, the engine was shut down and examined. Inflows of fuel under the external ring were observed.

At second starting, with the external ring secured, flame was noticed under the engine's body cone, as a result of which the engine was shut down.

A flow of fuel was established in the space under the body cone caused by a crack in the welded seams of the body.

Further tests cannot take place without eliminating this defect.

Ignition of fuel in the engines in the first and second cases occured normally.[1] /54

Our investigation group naturally had to eliminate all these bugs with great effort and at the expense of a significant amount of time.

On 22 August, the second DM-4s engine, No. 15, was installed in the wind tunnel. Ignition failed in the first four attempts. After adjustment of the electric ignition device, the engine did not ignite for three tests, and this was found to be caused by obstruction in the flow meter through which the fuel passed. On 29 August, the test of engine No. 15 continued. This time the engine ignited normally. Three tongues of flame were clearly visible whose centers were like connecting pipes guiding the gasoline to the burner. With an airflow speed of $\sqrt{tr} = 47$ m/sec in the working section and a fuel supply of 120 cm^3/sec, the jet was 1 to 1.5 m in length. The engine operated 3 minutes with fuel supply varying from 50 to 150 cm^3/sec. Five tests were conducted on 31 August. In the first, the engine did not start, but the four subsequent tests were normal.

Thus, day by day there were further improvement and testing of the DM-4s ramjet engines at SEIG MAI.

The measurements and visual observations conducted in the first tests permitted determination of the characteristics of the flame in the combustion chamber with various burners and introducing improvements in the distribution of the force pumps throughout the burner tubes.

All initial tests were conducted on two DM-4s engines Nos. 14 and 15, so as to establish the necessary corrections and definitely select the armature and force pump distribution system variations to introduce into the types of DM-4s motors Nos. 16 and 17 intended for flight tests, while avoiding intermediate alterations in the flight models.

Upon completion of the first stage of the tests, the operational characteristics of the jet engines were studied.

As a result of carrying out all the tests in the wind tunnel and making further improvements, the safety of the DM-4s engine was ensured, the fire-resistance of all components was proved and operational reliability in the engine was /55 established. Thus, through the cooperative work of the Moscow Aviation Institute and the Special Design Office, the DM-4s ramjet engines were prepared for flight tests on the YaK-7B aircraft.

At the same time, studies of these engines showed that the gas temperature in the combustion chamber and gas velocity were somewhat lower than calculation. Therefore, in the report on the test-stand studies one conclusion stated:

"Along with the tests of the DM-4s motor on aircraft, it is most necessary

[1] Scientific Archives of the Institute of History of Natural Sciences and Technology of the USSR.

to perform further work in improving it, especially in achieving complete combustion, since comparison of calculated and experimental temperatures shows that full combustion has still not been achieved."[1]

As a result of tests of the engines, work on equipping the YaK-7B was started. The following report indicates clearly the character of this work:

Report of Work Completed on the YaK-7B Aircraft No. 820803 with No. 105 PF Motor No. 45-32

23 February 1944. We the undersigned: chief factory engineer V. A. Romadin, Chief of section No. 6 N. S. Laptev for chief of factory quality control section G. A. Tsesarskiy and chief engineer B. A. Nikolayevskiy have prepared this report that the following operations have been performed on the aircraft at NKAP factory No. 482.

1. Suspension of auxiliary engines.
2. Connection of gasoline supply lines to the engines.
3. Installation of fuel system units (auxiliary pumps, stopcocks).
4. Arrangement of valve control.
5. Installation of electric ignition of the engines.
6. Installation of engine control instruments.
7. Equipping rear cockpit for observer.
8. Improvement of landing gear and pneumatic system.
9. Calibration of instruments.
10. Debugging according to the engineering control list.
11. Painting aircraft.

These operations were conducted in compliance with plans drawn up by the design office (chief: I. A. Verkulov) and according to instructions of chief aircraft engineer B. A. Nikolayevskiy.

All these operations were accepted by the factory quality control dept.[2]

In 1944, the YaK-7B aircraft underwent flight testing of its DM-4s engines /56 to further improve their ignition, combustion, stability and synchronized engine operation under one of the most experienced test pilots, Sergey Nikolayevich Aneshchenko. According to the report, the following results were achieved.

The DM-4s engines on the YaK-7 were fired in flight at top speed at altitudes up to 5000 m. The design of the DM-4s permitted in-flight shutdown and reignition. Operation was simple. In-flight engine control presented the fliers no difficulties. The engines operated on aviation gasoline from the same tanks as the main engine. Equal performance was obtained from both engines.

1 "Preliminary report on the tests of the DM-4s auxiliary engines in the AT-2 wind tunnel" (Predvaritel' nyy otchet ob ispytaniyakh dopolnitel'nykh motorov DM-4s v trube AT-2) 1943, p. 12.

2 Scientific Archives of the Institute of History of Natural Science and Technology of the USSR Academy of Sciences.

After this stage of flight tests, it was proposed to collect the detailed thrust characteristics for various parameters of engine design and its future improvement. Therefore, firing the engine and other problems of the first stage of the tests were carried out with arbitrary hardware and engine parameters and not those which appeared optimum on the basis of theoretical calculations and wind-tunnel tests. However, after the first stage was completed, flight tests were stopped due to a heavy discharge of fuel during operation of the engine. Fortunately, during one of the first-stage flights, i.e., during adjustment of the engines, a significant increase in the craft's speed was obtained through the operation of the air-breathing engines. This flight took place at 2340 m in altitude, where the maximum level speed of the test model of the YaK-7B without the DM-4s working was 460 km/hr. With the engine operating, the maximum speed increased by 53 km/hr, i.e., to 513 km/hr. The top speed of the YaK-7B without the auxiliary engines at a given altitude was 494 km/hr. Thus, the actual increase in speed was 19 km/hr. However, in evaluating this result, we must consider that both engines were suspended from the wings without fairing and that this suspension constitutes significant drag for both the engine and wing.

These results now seem understandably quite modest, but we cannot forget how important they were for that time.

Each research engineer and physicist knows how often new theories for invented machines prove incorrect upon experimental testing. A quarter century ago, everyone feared that this might be true of the ramjet engine theory. /57

The main result of test-stand and flight testing was that they proved the correctness of the theory and calculation methods put forth earlier, and thus showed that detailed structural development of the engine and the deepening of theory which was necessary to do so was a matter of government importance.

The legacy of B. S. Stechkin, Yu. A. Pobedonostsev and I. A. Merkulov was passed on to many strong scientific and engineering institutions. One of these grew out of the group headed by Mikhail Makarovich Bondaryuk, created in the first years of the war. The guiding spirit, along with M. M. Bondaryuk, was the remarkable scientist Sergey Mikhaylovich Il'yashenko. He presented brilliant undergraduate and graduate dissertations on deepening ramjet theory. I consider his monograph, prepared with M. M. Bondaryuk, to be the best in this field.

In those years, the ramjet's extreme fuel consumption frightened many scientists. Now, however, all seem to recognize that at flight speeds twice or more that of sound the ramjet is the most economical of engines. Its efficiency may substantially exceed 40 percent. This and the absence of loaded rotation parts will aid its prevalence in the future.

Translated for the National Aeronautics and Space Administration
by John F. Holman Co. Inc.
WASHINGTON, D.C. 20037
NASw-1497